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PROBLEM-FREE NUCLEAR POWER AND GLOBAL CHANGE*

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ABSTRACT

Nuclear fission power reactors represent a solution-in-principle to all aspects of global change possibly induced by inputting of either particulate or carbon or sulfur oxides into the Earth's atmosphere. Of proven technological feasibility, they presently produce high-grade heat for electricity generation, space heating and industrial process-driving around the world, without emitting greenhouse gases or atmospheric particulates. However, a substantial number of major issues currently stand between nuclear power implemented with light-water reactors and widespread substitution for large stationary fossil fuel-fired systems, including long-term fuel supply, adverse public perceptions regarding both long-term and acute operational safety, plant decommissioning, fuel reprocessing, radwaste disposal, fissile materials diversion to military purposes and – perhaps most seriously – cost.

We describe a GW-scale, high-temperature nuclear reactor heat source that can operate with no human intervention for a few decades and that may be widely acceptable, since its safety features are simple, inexpensive and easily understood. We provide first-level details of a reactor system designed to satisfy these requirements.

Such a back-solving approach to realizing large-scale nuclear fission power systems potentially leads to an energy source capable of meeting all large-scale stationary demands for high-temperature heat. If widely employed to support such demands, it could, for example, directly reduce present-day world-wide CO_2 emissions by two-fold; by using it to produce non-carbonaceous fuels for small mobile demands, a second two-fold reduction could be attained. Even the first such reduction would permit continued slow power-demand growth in the First World and rapid development of the Third World, both without any governmental suppression of fossil fuel usage.

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Global Change. The prospect of raising the space- and time-averaged absolute temperature of the terrestrial biosphere by ~1% during the 21st century by the combined direct and indirect effects of anthropogenic injection of "greenhouse gases" (principally carbon dioxide, CO_2) has given rise to proposed remedial actions directed to proscription of carbon dioxide injection.

Uncertain estimates suggest that increasing the current U.S. wholesale prices of carbon-based fuels by ~40% will suffice to suppress fossil fuel use to levels such that CO_2 injection-rates will be reduced to 1990 levels. (These 1990 injection-rates are believed, without genuine consensus in the scientific community, to be sufficient to adequately attenuate major environmental aspects of global warming.)

The economic implications of such price-based suppression of fossil fuel use are of very large-scale. For example, approximately 75 million barrels of oils presently are used per day, seasonally averaged. The recent 12 month-averaged cost of a barrel of oil is ~$20, so that the world's crude oil bill currently is ~$550 B/year. A 40% increment in this cost would amount to $220 B/year. When other fuels (principally coal and natural gas, at present) are also considered, the total proposed price-burden on all fossil fuels world-wide in order to suppress CO_2 atmospheric injection amounts to ~$400 B/year, at current costs and consumption levels.

(Approximately 25% of this fossil fuel price-burden would be borne by fossil fuel users in the United States, at an annual cost of ~$100 B. This amounts to ~1.4% of current U.S. GDP. At the current amortization rate for low-risk investments, it is equivalent to a one-time expenditure of ~$1.2 T.)

Large-Scale Nuclear Power Supply. Over the past four decades, nuclear fission power reactors have come into widespread usage throughout the world, particularly in the developed countries. Currently, France derives over 70% of its electricity from nuclear reactors, while Japan realizes more than 40% and the U.S. gains 20%. Nuclear-generated electricity in the U.S. presently has a *production* cost which very closely rivals that of the lowest-cost source, coal-fired plants (both of which *produce* electricity for ~$10/MW-hr, or 1 cent/kW-hr), when the best nuclear plants are compared to the best coal-fired ones. (Obviously, comparisons of best examples are most relevant; nearly arbitrarily poor examples of all major technologies usually exist, but are of little enduring interest.)

Nuclear power reactors are almost exclusively of the light water-cooled (LWR) type originally developed in the U.S. for plutonium production during World War II and adapted (e.g., via substitution of water for graphite as moderator) in the subsequent dozen years for raising steam of quality useful for Rankine cycle-based, turboalternator-implemented electricity generation. Other major adaptive steps taken included the use of isotopically-enriched uranium fuel (enriched in the U^{235} isotope from the naturally occurring level of 0.7% to 2.5-3.5% for greater fuel specific energy production and thus longer intervals between required refueling) and the elimination of designed-in safety deficiencies (e.g., the positive temperature coefficient-of-reactivity defect which was the proximate cause of the steam boiler-type explosion of the Chernobyl reactor).

Nuclear power reactors enjoyed widespread penetration of the electricity-producing marketplace during the first two decades after the advent of the first commercial nuclear plants, over the interval ~1957-77. At the time of the Three Mile Island accident in the U.S., official government projections were for exponentially advancing use of nuclear power through the year 2000, with ~500 GWe of installed capacity in the U.S. alone being a mid-range estimate for the end of the century. Such high electrical production levels in turn required more enriched uranium fuel than could be realized from existing reserves of uranium ore, necessitating the development of a breeder-type power reactor, one which could produce more fuel than it consumed.

Major breeder reactor development programs in the U.S., France and Japan have not met with outstanding technical or programmatic success. Furthermore, over the same interval (~1972-85), electrical power demand in the developed countries, which had been increasing rapidly for several decades (e.g., in the U.S. at a ~7% annual rate over 1947-72) dropped quite rapidly (e.g., to a recent ~1.5-2% annual rate in the U.S.).

The slumping increase-in-demand for electricity correspondingly diminished requirements for new electrical central-station capacity. Diminishing order-flow increased the unit costs of suppliers, many of whom did not move sufficiently quickly and vigorously to curtail their overhead costs. This effect was particularly marked for nuclear plant vendors, who were also burdened during this interval with a stream of demands by regulators for qualitatively and quantitatively enhanced safety features, demands originated in a plethora of minor accidents-and-incidents but focused in public perceptions by the Three Mile Island accident in 1979. These rapidly-escalating economic burdens, combined with the psychological impact of the major Chernobyl nuclear power reactor accident in 1986, sharply attenuated the demand for new nuclear power plants in most all of the advanced countries during the past decade – with the notable exceptions of France, Belgium and Japan, which seem to place high valuations on the energy supply-security implicit in nuclear-generated electricity.

Throughout this interval, the stiff economic incentives posed to electrical power plant suppliers selling fossil fuel-fired combustion units by order-of-magnitude-increased crude oil prices were motivating improvements in the thermodynamic efficiency with which such fuel is converted into electricity. Stalled for a half-century at 30-35% efficiency in converting thermal energy into electricity, Rankine cycle-based systems slowly crept toward 40% efficiency during the '80s. The introduction of combined Brayton and Rankine cycle combustion heat-to-electricity conversion systems during the last decade has seen conversion efficiencies climb swiftly toward 60%. Unsurprisingly, these efficiency record-setting combined-cycle systems also have recently set the economic pace in electricity production; they offer a *total unit energy cost* of ~$0.04/kW-hr, compared to $0.08-0.09/kW-hr for nuclear-generated electricity. (*Total unit energy cost* differs notably from *production cost* by properly including all charges involved in the generation of electricity including the capitalization of the generation facilities.)

This has resulted in the *de facto* cessation of nuclear power plant sales in most developed countries. World-wide, there were 437 nuclear power plants in operation at mid-year 1996, and 39 under construction. Since power-plant lifetimes are ~30 years and construction times are ~5 years, it's clear that the Earth's nuclear power plant population is not only not rising but isn't even in steady-state; rather, it'll decline rapidly to less than half of its current level, if present trends continue.

<u>What Is To Be Done?</u> Nuclear generation is the only large-scale, generally-available source of electricity which doesn't involve the release large specific quantities of CO_2 (i.e., of the order of a kg/kW-hr) into the Earth's atmosphere. If growth in electrical demand over the Earth as a unit is to continue at anything like recent rates and yet CO_2 emissions into the Earth's atmosphere are to remain constant or perhaps even decrease, only nuclear sources of electricity are *actually* available to fill the <u>annual energy gap</u> of *tens of thousands of terawatt-hours* which is thereby engendered, as soon as two decades hence. Renewable resources either are distributed in a quantitatively inadequate and geographically quite uneven manner. Such energy sources comprise less than 3% of total U.S. generation, after two decades of reasonably intensive government subsidies.

In this paper, we inquire as to whether and how nuclear fission-based electricity generation can *actually* contribute to maintenance of an advancing standard-of-living for people everywhere while attaining asymptotic concentrations of CO_2 in the atmosphere not greatly in excess of current ones.

<u>Constraints And Their Motivations.</u> We consider the following constraints on all *actual* 21st century nuclear power options to be essential ones, for reasons which we note only in passing, due to their generally obvious character:

- **Fuel Supply And Preparation.** Nuclear power reactors which may be fueled with inexpensive, widely-available fuel are the only ones which are of present interest. Any fuel chosen must be reliably available in sufficient quantity at reasonable extraction costs to give 10 billion people a First World energy standard-of-living for at least 1 century: 10 billion kW-centuries of electrical energy, or ~3 x 10^{29} ergs, or 300 tonnes of mass-energy, or ~300 kilotons of actinide element fissioned with 100% conversion to electricity. Furthermore, preparation of the fuel for reactor use must involve sufficiently simple operations as to form the basis of a genuinely world-wide free market for fueling services, one inherently resistant to cartel-formation and political restraints-of-trade.

- **Fueling Operations.** Reactors should not require re-fueling, once they have commenced operation – for reasons of economics, safety and of suppression of materials diversion. (Modern naval reactors operate without refueling for the 3-decade operational life of a submarine for reasons of economy and military operational availability, and there's no basic reason why civilian power reactors can't have this feature also.) All the fuel which a reactor needs during its entire operational life should be built into it, as it's manufactured. Reactor design and construction are thereby greatly simplified, due to elimination of the necessity to provide for opening, re-sealing and removing and installing fuel assemblies in an in-service reactor's core. Similarly, expensive and hazard-prone periodic refueling is obviated, and costly, risk-prone complications such as annual spent fuel handling, storage and transport to reprocessing sites are eliminated. Reactor design involving a minimum of moving parts is helpful in this respect.

- **Fuel Reprocessing.** Reprocessing of spent reactor fuel is unnecessary-in-principle for a nuclear energy economy, but provides a point at which fissile materials are inherently divertable to military uses, and burdens nuclear power generation with non-negligible economic and public-perceptual costs. Reprocessing therefore should be avoided to the greatest extent possible.

- **Radwaste Disposal.** Disposal of long-lived radioactivity generated in the course of operation of reactors of present interest should be performed in a manifestly safe and robust manner, so that the <u>exceedingly</u> low likelihood of entry of non-negligible amounts of reactor-generated radioactivity into the biosphere at <u>any</u> future time can be made reasonably clear even to the lay public.

- **Materials Diversion.** Fuel for reactors of present interest during all times in its existence, from manufacture through final-and-irreversible disposal, must be of a nature as to have no utility, regardless of quantity, for any military purposes without isotopic enrichment capability being exercised on it.

- **Operational Safety.** Reactors of present interest must be inherently incapable of suffering damage, no matter how seriously their controls should be mishandled by their operators. They must also be incapable of damage due to loss-of-coolant accidents of all degrees of severity. In addition, they should be highly immune to human misbehavior, ranging from insider sabotage through terrorist attacks to military actions. In no circumstances, no matter how abnormal, can they be capable of releasing significant quantities of radioactivity into the biosphere.

- **End-Of-Operational Life And Plant Decommissioning.** Reactors of present interest must be capable of inexpensive, low-risk decommissioning at end-of-operational-life, which must be required no sooner than following three decades of full-power-equivalent operation. Public safety (perceived and actual), resistance to materials diversion and ease of radwaste disposal during all phases of decommissioning are essential.

- **Public Perceptions.** The perceptions of the public regarding the suitability and desirability of nuclear power supply must be attended to, regardless of the closeness of connections with technical realities. In particular, the safety of all aspects of nuclear power generation must be made <u>obvious</u> to the general public, including the taking of risk-reducing steps which might not seem required from a technical standpoint and which might have non-negligible cost.

- **Economics.** Both the total unit energy cost and the energy production cost of nuclear electricity sources of present interest must be competitive with the best alternative fossil fuel-fired options.

<u>Resulting Basic Design Considerations.</u> We note that these constraints aren't independent, in that more than one may be simultaneously satisfied by a single design choice and that some particular ways of satisfying one may conflict strongly with satisfying another. The two largest issues are the economic and public perceptual ones, and thus we address them first.

Underground Siting. The public is rationally concerned about large, abrupt releases of radioactivity into the biosphere by nuclear power systems – and also is somewhat less reasonably worried about very small releases in quasi-steady state. Precluding both of these – but particularly the former – is of the greatest importance and moreover must be accomplished in an obvious fashion. We therefore consider siting of reactors deep underground to be desirable, moreover with only "long and slender," automatically-closed passages to the surface – and to the biosphere.[1] That large amounts of radioactivity cannot escape to the biosphere in the course of serious accidents from such locations may be made quite obvious. Such underground sites should also be made to be supportive of long-term "housing" of the reactor, after its operational life.

Minimum-Essential Operator Controls. All of the great accidents in nuclear power plants, without exception, have been due to maladroit control of the reactor by its human operators; operator errors also may constitute the primary factor in the larger number of much less serious accidents and incidents which erode public confidence. Therefore, we believe that it is essential that operator controls of reactors be reduced to the minimum essential ones, and that all possible uses of these should be incapable of inducing catastrophic reactor malfunction. Such a draconian step may be taken more easily if we construct reactors with a minimal number of moving parts.

Life-Cycle-Oriented Design. In order to be maximally economical, power reactors should be designed in a strongly life-cycle-oriented manner, with as much attention given to circumstances at and beyond end-of-operational-life and to initial construction as to the power-producing operation and maintenance interval. In particular, we believe that power reactors should be viewed as self-regulating, constant-temperature nuclear fission-powered heat sources which, once ignited, operate in a fully-automatic, highly-redundant thermostatic manner until either fuel exhaustion or commanded-shutdown occurs. We believe that a power reactor should be regarded – and designed – as a pressure vessel-clad fuel assembly with embedded power-regulating features and heat-removal features,

[1]We note that Andrei Sakharov independently reached this same basic conclusion in the aftermath of the Chernobyl accident, and strongly advocated underground siting of power reactors in his memoirs.

supplemented by means for highly redundant, entirely automatic heat rejection into a "can't fail" heat-sink. After final shutdown, nuclear afterheat associated with longer-lived beta-decay of fission products must be reliably removed.

Furthermore – an admittedly radical step – we believe that the reactor should also be regarded – and designed – as the long-term-stable burial cask of all of the radwaste products which it generates throughout its entire operational life, so that once it is emplaced and its fuel charge ignited, it is not thereafter maintained, disturbed or removed – for tens of millennia. This should be possible without large cost increments; indeed, we believe substantial life-cycle savings might be realized, relative to the LWR-centered nuclear fuel cycle.

Inexpensive, Standardized Construction. Mass production-oriented manufacture and emplacement/construction of standardized, extensively-evaluated nuclear power-plant designs is an essential feature of both economic and safe nuclear power systems. Mass production is rational in a world in which about 1 GW of electrical generating capacity must be added each week into the foreseeable future.

Salient Features Of A Point-Design. We have previously offered a conceptual-level point-design of a nuclear power reactor which we believe satisfies the constraints which we have stated above.[2] We recapitulate some of its salient features.

Use of a hard, or fast, neutron spectrum is essential to simultaneous attainment of the goals of no fuel reprocessing and no reactor re-fueling, due to strong absorption of slow neutrons by fission products. This fast neutron-spectrum design choice in turn facilitated the extensive use of high-Z, highly refractory materials in the baseline reactor core design, for such materials have unacceptably large impacts on the neutron economy of any thermal-spectrum reactor, but are eminently affordable in neutronic terms when using a fission-spectrum. Use of such materials permit very high-temperature reactor operation, e.g., coolant exhaust temperatures of $\leq 1200^{o}$ K, which in turn admits the possibility of high-efficiency, combined-cycle thermal-to-electric conversion of the heat outputted by the reactor.

We were unable to design a reactor with an inherent exceedingly large thermal coefficient of neutronic reactivity (~0.2%/^{o}K) over a narrow ($\Delta T \leq 100^{o}$K) temperature range – and yet such great "stiffness" of reactivity with material temperature variation at all points within the reactor's core is necessary for stable high-temperature reactor operation required for efficient conversion of reactor heat to electricity and for operational safety. We therefore endowed the reactor core as a whole with such an engineered-in feature, using a 3-dimensional lattice of liquid-lithium-bulbed thermostats to control the local material temperature via negative feedback on "local reactivity" implemented with liquid Li^6, a strong neutron absorber. Excessive local temperature causes the local introduction of additional Li^6, thereby reducing the local reactivity.

The reactor thus acts as a source of heat at a thermostat-specified high temperature at any heat-extraction rate up to its full-power rating, over any time-interval until its initial fuel-charge is exhausted or it is operator-commanded to shut down.

The ability to independently control reactivity at all points throughout the core on the basis of local material temperature permitted use of a propagating mode of nuclear fuel burn which is notably efficient. Leveraging the superiority of a fission-spectrum neutron economy, this fuel-burning mode simultaneously enables high (≥50%) burn-ups of entirely unenriched actinide fuels – either natural

[2] See, e.g., see http://www-phys.llnl.gov/adv_energy_src/ICENES96.html.

uranium or thorium – and the use of a comparatively small "nuclear ignitor" region of moderate (sub-weapons-grade) isotopic enrichment in the center of the core's fuel-charge.

We designed a highly redundant and fully automatic heat transfer system to prevent meltdown of the reactor core under any conditions.

We have suggested that this novel type of nuclear power reactor might be able to generate electricity at a total unit energy cost even less than that of combined-cycle gas. It uses essentially unenriched, as-mined actinide fuel, operated to high fuel burn-up without reprocessing – and thus accesses a huge, near-zero-cost fuel stockpile, one widely distributed geographically and of a magnitude sufficient to supply the entire human race at current U.S. levels of energy consumption for many centuries. Since spent fuel is intrinsically inaccessible, this type of reactor technology is therefore suitable for world-wide deployment, without concern for misuse of reactor products for military purposes.

We strongly suspect that <u>many</u> other designs – some significantly different from the one which we've developed – would also satisfy the constraints which we have suggested are necessary for universal acceptability of nuclear power.

<u>Conclusions.</u> <u>If</u> global climate change is recognized as a real phenomenon and <u>if</u> suppression of CO_2 emissions into the atmosphere is the means chosen to palliate its effects, then <u>either</u> world-wide energy production will decrease <u>or</u> else some major source of central-station generation – of heat and/or electricity – will be employed to fill the ever-expanding gap between growing energy demand (mostly in the developing world) and diminishing fossil fuel-based energy supply. At the present time, only nuclear fission-based central station technology is sufficiently industrially developed and operationally performance-proven to be a credible candidate for this gap-filler role.

However, nuclear power systems expressing current design, construction and operational practices have a substantial set of significant issues facing them. The aggregate effect of these issues has halted – indeed, has even reversed – the penetration of electricity markets by nuclear technology in most of the developed countries. They seemingly must be satisfactorily addressed if nuclear power is to be other than a niche player in the 21st century energy picture, i.e., if there is to be a low-risk gap-filler between rising energy demand and diminishing fossil fuel-fired supply.

In this paper, we have sketched what we believe to be satisfactory responses to these issues, and have given examples of how these responses may be expressed in an actual design for 21st century nuclear power reactors. We believe that <u>all</u> issues facing nuclear power – including the compelling economic and public perceptual ones – may be simultaneously addressed.

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